DYNAMIC MODELLING AND SIMULATION STUDY FOR THE GALILEO SPACECRAFT PULSED-MODE SPINUP / 400 N MAIN ENGINE BURN / SPINDOWN MANEUVERS

Che-Hang Charles Ih* & Elihu H. McMahon II*

* *Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California, 91109. USA*
Fax: (818) 393-7830, E-mail: Che-Hang.C.Ih.@ccmail.jpl.nasa.gov

ABSTRACT. Two Galileo dynamic models were developed to simulate the spinup / 400-N main engine burn / spindown maneuvers for the critical events of Jupiter Orbit Insertion (JOI) and Perijove Raise Maneuver (PRM). The dynamic interaction among the spin thruster pulsing frequency, science/magnetometer (SCI/MAG) boom flexible modes, and the propellant slosh modes were studied. The prediction of safe JOI was validated in flight. For PRM, however, the simulation results indicated that propellant unporting would occur if the original spin thruster duty cycle (1.3 sec ON / 3.9 sec OFF) was not updated. Based on further simulation results, a new duty cycle (0.9 sec ON / 0.9 sec OFF) was selected to prevent propellant unporting. Subsequent Galileo flight data indicated that PRM was executed successfully.

1. INTRODUCTION

Nearly 400 years after the Italian astronomer Galileo Galilei discovered Jupiter's major moons, the Galileo spacecraft was successfully inserted into Jupiter's orbit on December 7, 1995, and began its 23-month exploration of the planet and its moons. The spacecraft was designed, built and continues to be operated by NASA's Jet Propulsion Laboratory to investigate Jupiter's atmosphere, moons, and the surrounding magnetosphere. It is the first dual-spin planetary spacecraft (Fig. 1). The rotor (the spinning section) normally spins at 2.9 rpm to maintain the spacecraft stability and allow the science/magnetometer (SCI/MAG) boom to sweep about in order to perform magnetosphere experiments. The stator (the despun section) can be kept stationary to provide inertial pointing of the camera and other instruments. Also mounted on the rotor are the High-Gain Antenna (HGA), two low-gain antennas, two Radioisotope Thermoelectric Generators (RTG), the propulsion module, the star scanner, instruments for measuring fields and particles, and most of the computers and control electronics. The scan platform mounted on the stator carries the camera system and the instruments for atmospheric and moon surface chemical analysis, studying the gases, and measuring the radiation energy. The Radio Relay Antenna (RRA) and the atmospheric probe are also attached to the stator.

Galileo was launched on October 18, 1989, and began its six-year Venus-Earth-Earth-Gravity-Assist (VEEGA) trajectory. During this period, scientific observations were made of Venus, Earth, and the asteroids Gaspra and Ida. Accidentally, scientists found a small moon orbiting Ida, which was later named Dactyl. As a bonus, Galileo's imaging instruments also directly captured the impact of the fragment W of Comet Shoemaker-Levy 9 with Jupiter in July, 1994.

On July 13, 1995, the rotor and stator were locked together and the entire spacecraft spun up to 10.5 rpm for more gyroscopic stability. Galileo then released the atmospheric probe on a course for Jupiter. Following the probe release, the spacecraft fired its 400-Newton main engine for the first time to deflect its own trajectory for Jupiter orbit insertion. The probe descended into Jupiter's atmosphere on December 7, 1995, and transmitted valuable science data such as temperature, pressure, chemical composition, lightning, and radiant energy of Jupiter's atmosphere

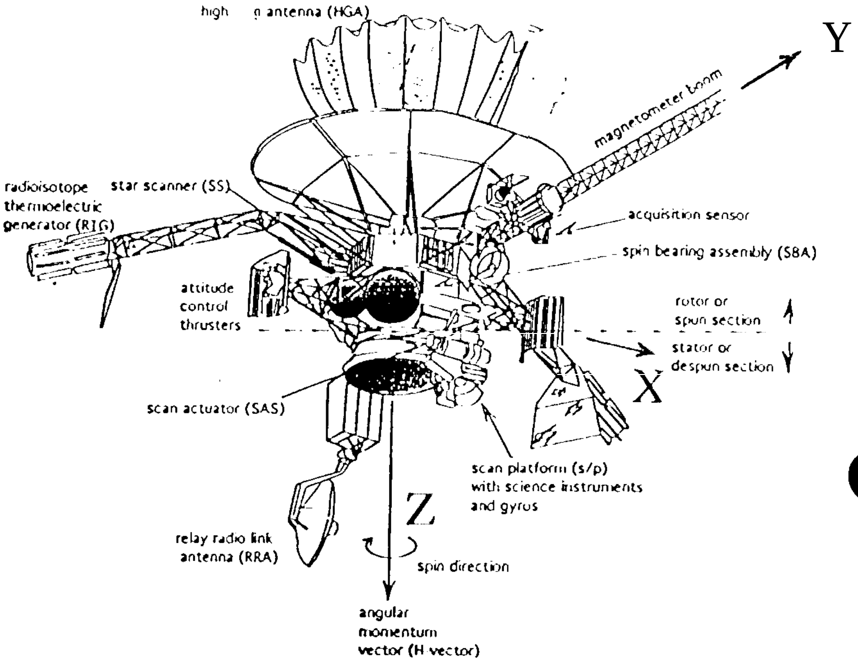

Figure 1. Galileo spacecraft

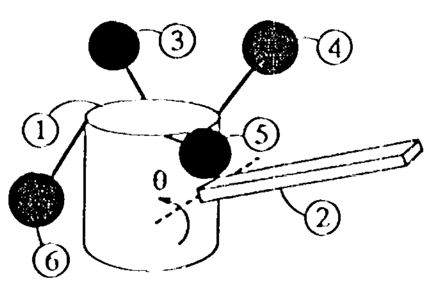

Figure 2. The 6-body Galileo model

back to the spacecraft. The spacecraft then fired its 400-Newton engine for 49 minutes (again at the spin rate of 10.5 rpm) to slow down and was successfully captured by Jupiter's gravity into Jupiter's orbit. For the following 23-month orbital tour, Galileo will travel in 11 different elliptical orbits around Jupiter. It will encounter Jupiter's satellite. Ganymede four times, Callisto three times, and Europa three times to perform close observations. It will also gather valuable data of Jupiter's magnetospheric and dust environment. On March 14, 1996, the spacecraft executed a Perijove Raise. Maneuver (PRM) to protect its instruments from being damaged by Jupiter's radiation. To perform this maneuver, the spacecraft spun up to 10.5 rpm and fired its 400-Newton engine for the last time.

As mentioned above, for critical events such as atmospheric probe release and 400-N main engine firing, the rotor and stator were locked together in all-spin mode and the entire spacecraft spun up to 10.5 rpm to enhance gyroscopic stability, avoid propellant unporting, and preserve, SCI/MAG boom integrity. Since thruster test results showed that prolonged continuous firing of the spin thrusters is not acceptable, the spinup/spindown maneuver had to be done in pulsed mode. Examination of the dynamic interaction among the spin thruster pulsing frequency, SCI/MAG boom flexible. modes, and the propellant slosh modes was essential to ensure the SCI/MAG boom structural integrity and to avoid mission catastrophic propellant unporting.

To this end, two Galileo models were developed and the complete spinup / 400-N engine burn / spindown maneuver sequence was simulated for the critical events of JOI and PRM. The prediction of safe JOI was validated in flight on December 7, 1996. For PRM, however, the simulation results showed that although the SCI/MAG boom structural integrity was ensured, propellant unporting would occur (due to low propellant level) if the original spin thruster duty cycle (1.3 sec ON / 3.9 sec OFF) was not updated. A group of new duty cycles which correspond to till-uster pulsing frequencies that are higher than the propellant slosh frequency range were then proposed. Simulation results demonstrated that propellant unporting problem could be avoided if any of these duty cycles were used. The project management selected the proposed 0.9 sec ON / 0.9 sec OFF duty cycle and PRM was successfully executed on March 14, 1996.

2. DYNAMIC MODELLING AND SIMULATION TOOLS

For the model development time.'is a tradeoff between the high fidelity and the feasibility of running long and complex simulation. With these considerations, two rigid body models -- a 6-body model and a 7-body model were developed [1][2]. First of all, for the maneuvers considered in this study, the spacecraft is in the "fill-spin" mode where the rotor and stator are locked together and spin up / spin down as one body. This configuration simplified the model development tremendously. As shown in Fig. 2, the 6-body model consists of the following six bodies. The base body (Body 1) is made up of the dry rotor (contains no propellant), the stator, and the scan platform. Body 2. is the SCI/MAG boom. It is attached to the base body at the rotation damper hinge point. Nutation damper stiffness, damping and stiction effects are modeled. Bodies 3 and 5 are the fuel slugs, and Bodies 4 and 6 are the oxidizer slugs. The propellant slug mode.1 is shown in more detail in Fig. 3. Movements of the slug can be realized by two rotations of the imaginary link connecting the slug and the tank center. The azimuth motion is the rotation ψ on the spin plane about an axis parallel to the space.cfaf(z-axis (Fig. 1) and passes through the tank center. The elevation motion is the rotation θ out of the spin plane and is located by the azimuth motion. Note. that this propellant slug model assumes 100% participation of the fuel in the slug motion. Thus, the model is conservative. However, for low fuel fill-fractions, this model matches very well with Hughes experimental data [3]. In all, the. 6-body model has 15 degrees of freedom (DOF): 8 DOF for the propellant slugs, 6 DOF (3 translational, 3 rotational) for the base body, and 1 DOF at the.nutaticm damper hinge point. Another conservative aspect of this model is that zero fuel slosh damping, is assumed.

The 6-body model does not include any structural flexibility, but it IS important to Consider the flexible modes which will be excited by the pulsing frequencies of the spin thrusters (below 1 Hz) during spinup/spindown. It is found that the. modes with frequencies below 1 Hz are contributed by the. SCI/MAG boom only. To this end, a SCI/MAG boom two-rigid body model was generated [4] that resulted in a 7-body mode.1 for the spacecraft. Bodies 1, 3, 4, 5 and 6 are exactly the same as those in the 6-body model. Body 2 represents the science boom and magnetometer canister, and Body 7 rc.presents the magnetometer boom, as shown in Fig. 4. Body 2 is attached to the base body (Body 1) at the nutation damper hinge point. Again, nutation damper stiffness, damping and stiction effects are modelled. Body 7 and Body 2 are connected by springs to provide a hinge with 3 rotational DOF. The masses, moments of inertia, center of mass locations of the two bodies, hinge locations, and Spring stiffness were selected such that boom modes up to 2.2 Hz could be reproduced by this mass-spring model. Two mode.s with frequencies below 1 Hz arc. shown in Fig. 5. The 0.124 Hz mode (rotation about x-axis) would be excited by the 400-N engine burn. The ().864 Hz mode (rotation about z-axis) would be excited during spinup/spindown. With 3 more DOF for the hinge connecting Body 2 and Body 7, the 7-body model has 18 DOF. It was used to examine the interaction among the spin thruster pulsing frequency, SCI/MAG boom flexible. mode.s, and propellant slosh modes. Once it was demonstrated that the SCI/MAG boom flexibility did not have any adverse effect on the responses of the dynamic variables analyzed, the subsequent analysis about the propellant unporting was performed using the 6-body model.

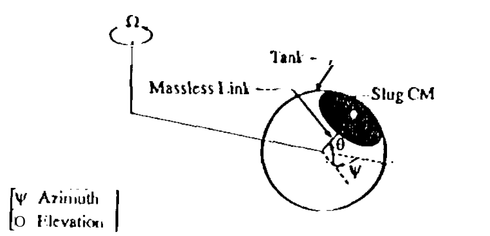

Figure 3. Galileo propellant slosh model

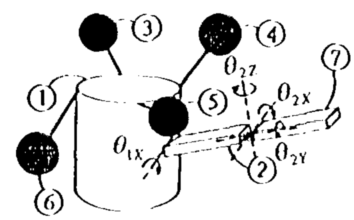

Figure 4. The 7-body Galileo model

Several modelling and simulation tools were used for this study. The dynamic models were \I,cIIc.rate.d by SD-EXACT [5], a software tool that utilizes symbolic equation manipulation techniques to generate the full nonlinear equations of motion for dynamic systems consisting of hinge-connected rigid bodies in a "tree" structure. The Galileo model fits perfectly in this category. It uses as inputs the tress and moment of inertia of the bodies, center of mass to joint position vector, type, of hinge, hinge axis, etc. In return, it generates the subroutines that code the full nonlinear equations of motion, calculate s the system angular momentum and rotational kinetic energy, etc. Subroutines for calculating space.claf(center of mass velocity, coordinate transformation, unit vectors of the space.craft z-axis and angular momentum in inertial frame, matrix multiplication, data output, etc. were written in FORTRAN. The main program was written in ACSL (Advanced Continuous Simulation Language) [6] which is a very useful tool for simulating systems described by time-dependent, nonlinear differential equations. The main program defines various parameters, calculates forces and torques and sends them to the SD-EXACT subroutine SDNSIM. SDNSIM then generates derivatives of dynamic variables for the main program to integrate.. A 4th order Runga-Kutta algorithm was used for integration with simulation step size set at 10 msec. Data were collected at 1 sec intervals. MATLAB was used for plotting and analysis,

(a) 0.124 Hz mode -- rotation about x-axis *(b) 0.864 Hz mode -- rotation about z-axis*

Figure 5. Two lowest frequency modes of Galileo

3. DYNAMIC SIMULATIONS OF THE SPINUP/400 N ENGINE BURN/SPINDOWN MANEUVERS

Among the many simulation cases conducted in this study, only the representative ones are presented. There were two parameters varied in all the simulations -- the spacecraft fuel fill-fractions (FF) and the spin thruster duty cycle. To be more conservative, large initial wobble (12 to 16 mrad) was chosen. For all of the case.s, the initial conditions were made to correspond to zero initial nutation stale. The dynamic responses for each case. were depicted in eight subplots, For convenience of discussion, the definition of each subplot are given below:

(a)-- spin rate time history in rpm
(b)-- angle between the H-vector and the spacecraft z-axis, a combination of the nutation (the damped periodic component) and wobb le (the non-periodic component)
(c)-- lateral and axial (along spacecraft z-axis) ΔV of the spacecraft center of mass
(d) -- H-vector perturbation (attitude perturbation)
(e)-- SCI/MAG boom deflection at the nutation damper hinge point
(f)-- SCI/MAG boom torque at the nutation d amper hinge point
(g) -- azimuth slosh excursions for all the four propellant slugs (plotted together)
(h) -- elevation slosh excursions for all the four propellant slugs (plotted together)

3.1 Simulation of the JOI and PRM Sequences Using Original Thruster Duty Cycle

The sequence involves a spinup to *10.5* rpm, *a* 10-minute wait, a 45-minute 400-N engine burn, and a 60-minute wait that was followed by the spindown to lowspin. The fuel FF used for JOI (Case [illegible] of these maneuvers. Spinup/spindown was executed using the original spin thruster duty cycle (1.3 sec ON / 3.9 sec OFF). For both cases, the 6-body model was used (mass properties are different due to different fuel FFs).

The responses for Cases 1 and 2 are plotted in Figs. 6 and 7, respectively. The execution of the spinup / 400-N engine burn / spindown JOI and PRM sequences is obvious from Subplots (a) and (b) of each figure. The sudden jump in wobble in Subplots 6(b) and 7(b) is expected due to the sudden jump of the SCI/MAG boom deflection at the nutation damper hinge point (Subplots 6(c) and 7(c)) caused by the 400-N engine burn. The magnitude of boom deflection and wobble jump is inversely proportional to the fuel FF, as expected. The result of the 400-N engine burn is evident in the huge axial ΔV (Subplots 6(c) and 7(c)). Again, the lighter the spacecraft, the larger the axial **ΔV.** Attitude perturbation (Subplots 6(d) and 7(d)) is within 1 mrad for all cases. Also as expected, boom torques (Subplots 6(f) and 7(f)) are proportional to boom deflections. For the propellant slosh motion in all cases, the azimuth slosh mode is excited during both spinup and spindown while the elevation slosh mode is excited significantly during the 400-N engine burn.

The large propellant slosh excursions raised the concern of propellant unporting, that is, the propellant ports were not completely covered. Unporting would be mission catastrophic. In order to best illustrate the propellant unporting situation, the propellant slosh motion of all four propellant slugs are plotted in the azimuth-elevation space together with the unporting boundary (the dash lines) in Figs. 8 and 9 for Cases 1 and 2, respectively. Any combination of the azimuth and elevation that is outside the boundary will cause unporting. Unporting boundary is directly

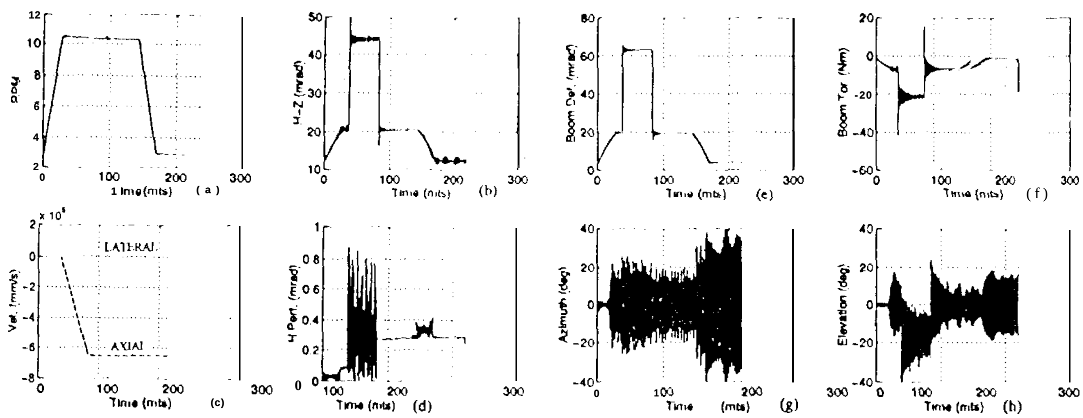

Figure 6. Spacecraft dynamic responses for the JOI case (Case 1, 31% fuel FF)

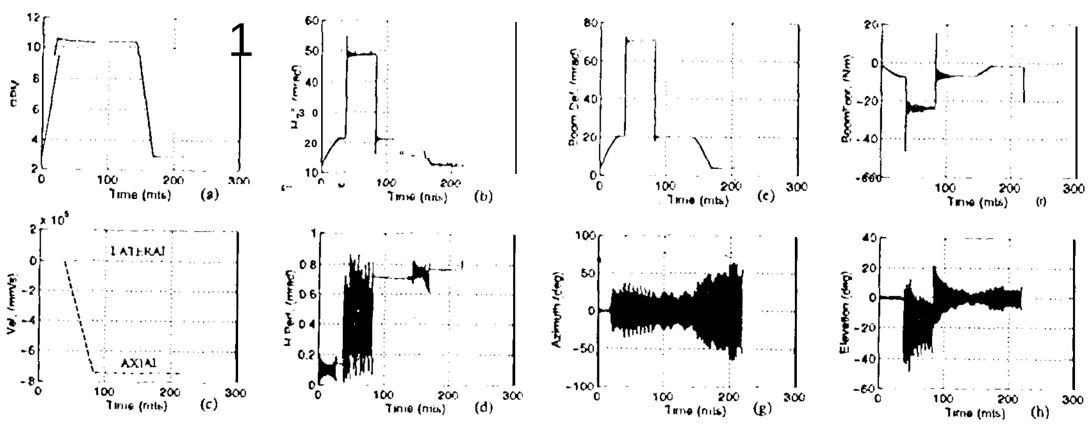

Figure 7. Spacecraft dynamic responses for the PRM case (Case 2, 11% fuel FF)

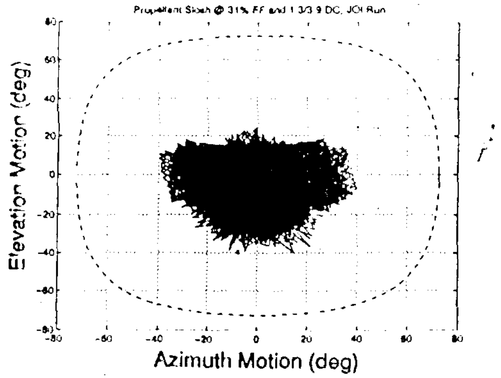

Figure 8. Propellant slosh motion for the JOI case using the original spin thruster dilly cycle (Case 1, 31% fuel FF)

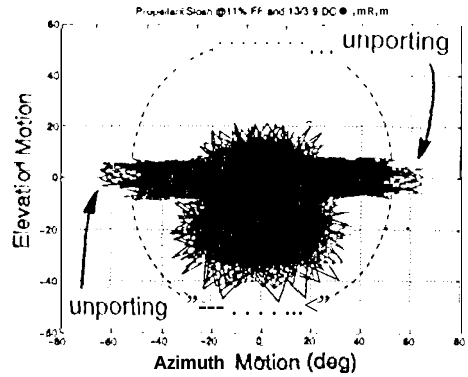

Figure 9. Propellant slosh motion for the PRM case using the original spin thruster duty cycle (Case 2,11% fuel FF)

related to the fuel FF, and is determined from the equations derived in Ref. 7. **As** expected, **the** boundary shrinks as the fuel becomes less because fuel slugs become smaller, and the amplitude of slug motion allowed is more limited in order to cover the propellant port. 11 is shown in Fig. 8 that fuel unpin ting is not a problem for JOI. For PRM, however, unporting would occur after spindown if the original spin thruster duty cycle was not updated, as can be seen from Fig. 9. The peak azimuth amplitude was about 65° while the azimuth unporting boundary was about 52°.

3.2 Simulation of the Spinup / 400 N Engine Burn/Spindown Sequence Using Original Thruster Duty Cycle Considering SCI/MAG Boom Structural Flexibility

The purpose of this study is to incorporate the flexibility of the SCI/MAG boom into the analy sis and reexamine the interactions among the thruster pulsing frequency, SCI/MAG boom flexible modes, and the p ropellant slosh modes. Therefore, the 7-body 1)1 odel was used. In order to characterize the effect of the boom flexibility, there is a 6-body counterpart (Case 3) for comparison with the 7-body case (Case 4). Fuel FF was chosen to be 1 1%. The sequence consisted of a spinup to 10.5 rpm, a **5** minute firing, of the 400-N" engine, and a spindown back to **2,.9** rpm. Spinup/spindown was executed using the original spin thruster duty cycle (1.3 sec ON / 3.9 sec 01:19.

The dynamic responses for the 6-body case (Fig. 10) and 7-body case (Fig. 11) arc extremely c1osc, dcmonstl-sting that even for small fuel FF, the effect of SCI/MAG boom flexibility on the propellant slosh excursion and other dynamic responses is very small. The hinge deflections about x-, y-, and z-axis (Fig. 12) at the. hinge connecting SCI and MAG booms are also reasonable and small. Hence, it is sufficient to use the 6-body model to characterize al] the

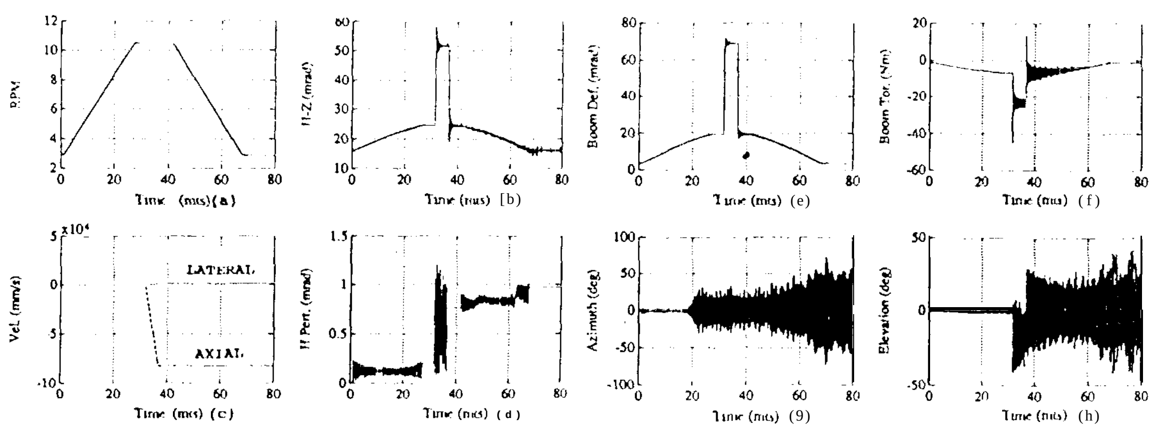

Figure 10. Spacecraft dynamic responses for Case 3 (6-body)

dynamic interactions. These dynamic responses were delivered to JPL's Structure Division to conduct load analysis for all critical elements of the SCI/MAG boom. It was concluded that the boom structural integrity was assured for the load of this critical maneuver [8].

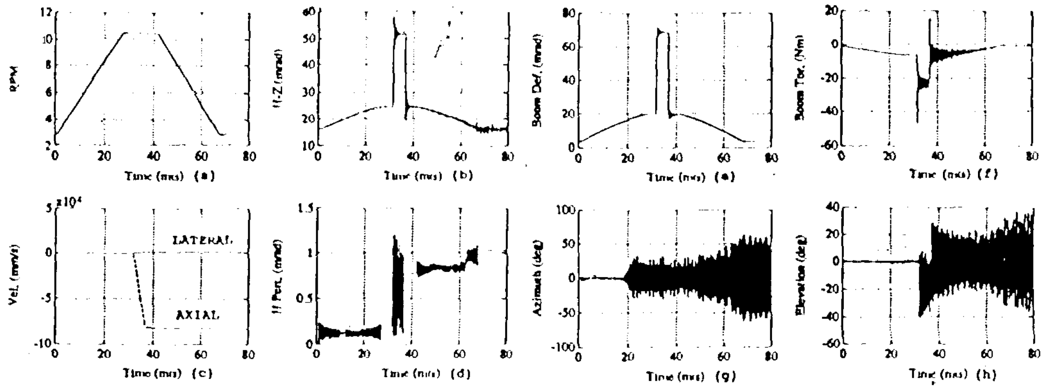

Figure 11. Spacecraft dynamic responses for Case 4 (7-body)

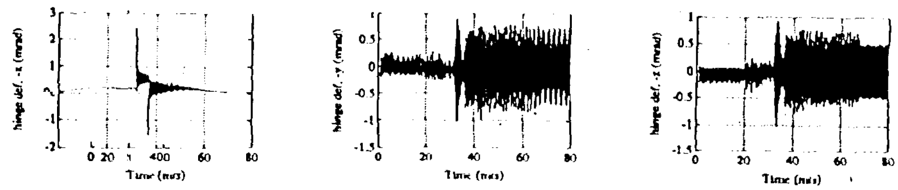

Figure 12. Spacecraft dynamic responses for Case 4 (7-body)

3.3 Simulation of the PRM Sequence Using New Thruster Duty Cycle -- Solution to the PRM Propellant Unporting Problem

As shown in Fig. 9, the propellant unporting problem occurred in the azimuth slosh excursion which was excited by the spinup/spindown process, not by the 400-N engine burn. Even more interesting is the fact that for both spinup and spindown, the azimuth slosh excursion started to be excited when the spin rate reached about 9.2 rpm (compare Figs. 7(a) and 7(g)). This phenomenon matched very well with the theoretical result. The pulsing frequency associated with the original spin thruster duty cycle was $2\pi / (1.3 + 3.9) = 1.2083$ rad/sec. Based on Hughes experimental data [3], the slosh frequencies for 11% fuel FF case are:

Azimuth frequency	= 0.3823 rad/sec	at 2.9 rpm
	1.3843 rad/sec	at 10.5 rpm
Elevation frequency	= 0.8035 rad/sec	at 2.9 rpm
	1.8229 rad/sec	at 10.5 rpm

Note that slosh frequencies increase linearly with the spin rate [1]. Between low spin (2.9 rpm) and high spin (10.5 rpm), the spin thruster pulsing frequency resonated with the slosh frequency (primarily the azimuth excursion because it was in the same direction as the spin of the spacecraft). The spin rate at which the resonance occurred was calculated as

$$\left(\frac{1.2083}{0.3823}\right)(2.9) = 9.166 \text{ rpm}$$

Hence, the violent azimuth excitation starting around 9.2 rpm was not surprising. One solution to this propblem was to raise the spin thruster pulsing frequency higher than the propellant slosh frequency range so that the resonance between the two can be avoided. The following duty cycles, 0.9 sec ON / 0.9 sec OFF, 0.5 sec ON / 0.5 sec OFF, 0.5 sec ON / 1.0 sec OFF, 0.5 sec ON / 1.5 sec

OFF, all satisfy the above, constraint. Excellent simulation results were obtained using these duty Cycles, leaving ample pad from the propellant unporting boundary. After consulting with the Retro Propulsion Module Subsystem, the Project selected 0.9 sec ON / 0.9 sec OFF. For this simulation case (Case 5), the motion of all four fuel slugs were plotted in the azimuth-elevation space together with the unporting boundary in Fig. 13. The peak azimuth amplitude was about '24°, well within the azimuth unporting boundary of 52°.

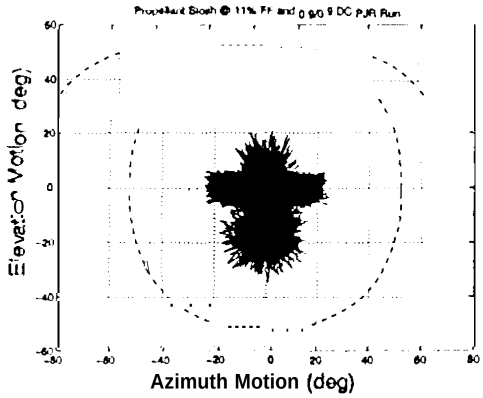

Figure 13. Propellant slosh motion for the PRM case using the new spin thruster duty cycle of 0.9 sec ON / 0.9 sec OFF (Case 5)

4. CONCLUSIONS

The dynamic interaction among the spin thruster pulsing frequency, SCI/MAG boom flexible modes, and the propellant slosh modes of the Galileo spacecraft was studied through simulation for the JOI and PRM maneuvers involving the spinup / 400-N engine burn / spindown sequence. The prediction of safe JOI based on the simulation results was validated in flight. PRM was also executed nominally on March 14, 1996 using the 0.9 sec ON / 0.9 sec OFF new spin thruster duty cycle proposed and verified in this study. This simulation study assured the spacecraft structural integrity and successfully solved a catastrophic propellant unporting problem.

ACKNOWLEDGEMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to thank Gurkirpal Singh and Walter Tsuha for their contribution and valuable discussions.

REFERENCES

1. G. Singh, "Design of Galileo Pulsed-Mode High-Spin (10.5 rpm) Spinup Maneuver", JPL Internal Memo 343-91-531, August ?, 1991.
2. C. Ih, "Galileo Pulsed-Mode Spinup Dynamic modelling and Simulation Analysis Considering SCI/MAG Boom Structural Flexibility", JPL Internal Memo GLL-01 VI-92-464-CC], September 11, 1992..
3. A. D. Challoner, "Final Report: The Identification of the Galileo Spinning Propellant Elevation Slosh Mode Parameters", Hughes Ref. No. 4J11 .10/ 1961, April, 1988.
4. W. S. Tsuha, "Galileo Science/Magnetometer Boom -- Mass-Spring Model", JPL Internal Memo 3542.-92,-2,11, April 23, 1991.
5. SD/EXACT and SD/FAST User's Manual, Version 87/4/6, Symbolic Dynamics, inc.
6. Advanced Continuous Simulation Language Reference Manual, Mitchell & Gauthier Associates Inc..
7. G. Singh, "Galileo Propellant Unporting Characteristics During the 400 N Engine Burn", JPL Internal Memo 343-91-478, July 12, 1991.
8. W. S. Tsuha, "Galileo Science/Magnetometer Boom Structural Integrity for 10.5 rpm Spinup/ 400 N Engine Burn/Spindown", JPL Internal Memo 3542-9 ?-395, August 3, 1992.